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Stand Level Compatible Diameter Distribution Models for Red Oak-sweetgum Complexes on Minor Stream Bottoms in the South

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STAND LEVEL COMPATIBLE DIAMETER DISTRIBUTION MODELS FOR RED OAK-SWEETGUM COMPLEXES ON MINOR STREAM BOTTOMS IN THE SOUTH

By

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Southern bottomland hardwood forests lack effective growth and yield predictive models primarily due to the complexity of the ecosystems. These models are important tools for relative comparison of management schemes and making sound management decisions to obtain optimal future yields. Starting in 1982, 150 red oak-sweetgum bottomland hardwood growth and yield plots were established in northern and central parts of Mississippi. These plots were remeasured in 1988, 1992, 1993, 2005, 2006, and 2007 along with the addition of new plots. A diameter distribution model was developed from stand level component equations constructed in a previous study (Iles 2008; Schultz et al. 2010). The equations created performed well when testing the predicted survival and diameter growth against the observed data. The resulting growth and yield system will be a basis for better decision making in the comparison of management alternatives as well as increased conservation and efficient utilization of wood products.

DEDICATION

I would like to first and foremost dedicate my work and time to Jesus Christ. I know if it was not for His help and the abilities He has given I would not have been able to complete this task. I hope that all I do is done in His name.

To my wife who has been with me throughout this entire project. I cannot thank her enough for all the love, support, and strength she has given me during this time as well as being able to put up with me when I would become disheartened.

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CHAPTER I

INTRODUCTION

Bottomland hardwood species compose one of the most important renewable timber resources in the South (Perkins et al.1994) and support a significant integrated solid wood industry composed of growers, procurement, processing, manufacturing, and marketing components. Forest industry is unique in that its capital is also its product or forest yield, creating a need for a balance between yield and the production process (Clutter et al. 1983). In order for this balance to be achieved, proper management techniques must be employed. Growth and yield models are an important management tool used for short- and long-term predictions of total stand or individual tree volumes by product and diameter size class (Avery and Burkhart 2002). Whether growth and yield models are used at stand or individual tree levels, their purpose is to estimate the future characteristics of stands (i.e. volume, basal area, number of trees per unit of area) at a specified point in time (Avery and Burkhart 2002).

Problem Statement

The decision making process employed in determining sound management strategies for obtaining future yields and objectives is the primary factor in landowner benefits and the sustainability of the forest resource and broader environment. Growth and yield models assist in predicting the outcomes of management decisions and comparing the benefits of alternative scenarios. Growth and yield models have been developed for a variety of species utilizing various tree or stand characteristics. Models that have been developed focus on species that are found in pure natural stands or plantations which are common (McTague et. al. 2006) but models for naturally regenerated, even-aged, mixed species hardwood stands are few (Roeder 1984). One reason for this scarcity is the species complexity and variation of the Southern hardwood forest compared to pine forests and the resulting difficulty of predicting growth in these stands (McTague et al. 2008). On the other hand, even-aged individual species models have been developed for economically important pine species like loblolly (Pinus taeda L.) (Amateis and Burkhart, 1981; Matney and Farrar, 1992), slash (Pinus elliottii Engelm.) (Zarnoch et al., 1991), and longleaf (Pinus palustris Mill.) (Farrar and Matney, 1994) pines (Schultz et al., 2010). Diameter is an important characteristic in building a growth and yield model, and the estimation of its distribution is essential in illustrating stand properties (Bailey and Dell 1973) and calculating future volumes and values by product.

Objectives

The purpose of this study was to develop distance independent individual tree diameter growth and survival models for red oak-sweetgum complexes on minor stream bottoms in the South. The resulting models are used to produce growth estimates for tree list(s) derived from existing inventories by species, size class, product, and grade. In the case where users can only supply mean diameters and surviving trees by species, initial tree lists are generated using diameter distribution recovery procedures. These equations were incorporated into the existing stand model available at www.timbercruise.com (Download Center, Growth and Yield Models). When they are incorporated into the existing stand model, parameter free least squares methods are implemented to reconcile the individual tree model with the existing stand level models.

Literature Review

Growth and yield prediction systems may be generally categorized as stand level, diameter distribution, or process model approaches. Stand level models may be constructed as normal (full stocking) or variable density. Diameter distribution models have been created for 1) distance-dependent and distance-independent individual tree models (Avery and Burkhart 2002), 2) parameter recovery (Matney and Sullivan 1982) and direct parametric prediction models (Clutter et al. 1983), and 3) least square recovery or parametric free models (Matney and Farrar 1992). Process models (Larson and Scott 2010) are typically individual tree models developed on the basis of responses to environmental and physiological factors. Some of these systems have been generated for individual species or pure stands and others for mixed species stands.

Individual Tree Equations

Individual tree models are commonly linked to a computer program that simulates the growth of an individual tree and aggregates growth over the entire stand (Avery and Burkhart 2002). Individual-tree models can be divided into two types. Distance independent models project tree growth either individually or by size class and typically consist of three basic components: (1) diameter-growth, (2) height-growth, and (3) mortality (Avery and Burkhart 2002). In distance-dependent models, the initial stand conditions are input or generated, and each tree is assigned a coordinate location for the calculation of distance to neighboring trees and competition indices. Tree growth is simulated as a function of the input and generated variables. In order for per acre yield estimates to be obtained, individual tree volumes must be summed and multiplied by an expansion factor PTAEDA2 model (Avery and Burkhart 2002) is an example of a distance-dependent individual-tree growth and yield model.

Amateis et al. (1989) circumvented the necessity of knowing exact tree location in the distance-dependent PTAEDA2 model by substituting a distance-independent measure of competition into its functional forms (Avery and Burkhart 2002). They created a measure of competition from the ratio of quadratic mean diameter (QD) at diameter breast height (dbh) and individual tree dbh, where the stand QD was computed from basal area and number of trees per unit area. Simulators for individual tree models use a variety of equations in order to predict factors such as diameter, basal area increment, height increment, and mortality rate (Hasenauer et al. 1998).

Perkins et al. (1994) developed a distance-independent individual tree growth and yield model for bottomland hardwoods in the minor stream bottoms of Mississippi. Individual tree basal area growth multiple linear regressions were developed using weighted least squares methodology which corrected potential problems dealing with heteroscedasticity of residuals. Mortality over all species was predicted by using multiple regression followed by allocating mortality to diameter classes and finally to species groups within each diameter class.

Hasenauer et al. (1998) examined the simultaneous nature of multivariate attributes in individual tree growth equations. This modeling approach produced more biologically logical growth equations by allowing simultaneous predictions. Because individual tree modules are primarily based on multivariate attributes, they found that estimating the asymptotic covariance of predictions in simultaneous regression techniques was an advantage.

McNab and Lloyd (1999) explored the relationship of diameter growth of individual trees with variables such as tree size, competition, and site factors. They looked at 11 major hardwood tree species and found that five-year periodic diameter increment was highly correlated with variables related to tree size and competition but less correlated with site variables.

Diameter Distributions

Diameter distribution models have become an important contribution in making sound forest management decisions (Cao 2004). Diameter is commonly associated with many other variables in forestry such as volume, value, conversion cost, and product, and this association is important economically and biologically (Bailey and Dell 1973). Mathematical functions are used to develop diameter distribution models, which represent the relative frequency for each dbh class that is encountered. The two most commonly used forest diameter distributions are the beta and Weibull functions (Avery and Burkhart 2002). It is important when selecting a function such as the Weibull to take in account the desired statistical effectiveness and ease of adaptation to computing applications (Bailey and Dell 1973).

The Weibull distribution has been used for modeling biological distributions such as the diameter distribution of forest stands (Zutter et al., 1986; Matney et al., 1990; Koger 1994). The Weibull is similar to the Normal distribution but has properties that allow greater flexibility with being left or right skewed (Koger 1994). The Weibull distribution can be a two- or three-parameter model, and a key component of using the Weibull is in estimating the parameters correctly. Cao (2004) created and assessed two new methods of predicting the parameters of Weibull functions: the maximum likelihood estimator (MLE) regression and the cumulative distribution function or (CDF) regression. These two methods ranked the best among six methods tested.

Matney and Farrar (1992) developed a simulator for thinned and unthinned loblolly pine (Pinus taeda) plantations in the Mid-Gulf south region. This simulator used a three-parameter Weibull distribution to produce a tree list. A weighted constrained least squares diameter recovery system (Matney et al. 1990) allocated mortality and growth to the tree list with constraints such that quadratic mean diameter (QD) and arithmetic mean diameter (AD) equal predicted stand level QD and AD.

Mengel and Roise (1990) developed a diameter class matrix model for southeastern coastal plain bottomland stands. The matrix model projects the future stand diameter distribution based on a matrix of probabilities and current diameter distribution. They suggest that the most appropriate use for this type of modeling would be for short term inventory updating. The disadvantage of the matrix model is its inflexibility of projection periods.

In order for a diameter distribution to be balanced it must contain a smooth geometric progression of the number of trees in diameter classes along with the ratio of the number of trees in a given diameter class (Bare and Opalach 1988). Bare and Opalach reexamined the 1974 growth and yield model developed by Adams and Ek (1974). They concluded that when using the Weibull distribution it is important to select appropriate maximum tree size limits and maximum tree size and per-tree price assumptions when applying the distribution to uneven-aged stands.

R. L. Bailey (1980) was first to connect diameter-distribution models to individual tree models (Qin et al. 2007). Qin et al. (2007) describe the links between a diameter distribution model and both an individual tree model and a whole stand model.

They review two scenarios; one, where a tree list is available and the other, where age, QD, and AD are available. Different paths for estimating mortality and growth throughout the scenarios are presented. Results showed that it was possible to effectively link individual-tree models and diameter distribution models.

CHAPTER II

METHODS AND MODELING

The original study, made possible through a grant from the U.S. Forest Service Center for Bottomland Hardwoods Research, consisted of 150 permanent growth and yield plots established in 1981. The plots were located throughout the north and central parts of Mississippi in primarily old field red oak-sweetgum stands on minor stream bottoms. Minor stream bottoms are defined as floodplains and terraces formed from local soils (Hodges and Switzer 1979). In 1988, 144 of the original plots still available were remeasured, and in 1992 and 1993, 115 of the original plots were remeasured. Forty new plots were established to replace plots lost to damage and harvesting. To obtain a minimal number of plots for developing a sound preliminary stand level growth and yield model, 31 temporary plots were installed in 1994.

Plot locations were selected to represent a broad range of site conditions, qualities, and ages (Table 1) under a defined set of criteria. Plots were selected from even-aged stands in Alabama and Mississippi occurring in river, creek, and other bottoms but not on lands occurring between the Mississippi River and its levee system nor from the loessal hills region of wind deposited soils along the eastern edge of the Mississippi River Delta. Stands were required to be undisturbed from cutting or severe damage (insect, wind, fire, beaver, etc.) for at least the last 20 years and unlikely to be disturbed for the next 10 years. Circular plots were established with minimums of 30% red oak basal area, 20 years of age, 50 measurable trees of 3.5" dbh or larger and 60 ft^2 total basal area. Minimum plot size was 0.1 acre and maximum plot size was 1.0 acre.

Data History

Starting in 2005, 86 of the existing original permanent plots were remeasured, and 72 new plots were established to produce a total of 158 plots for measurement. Over the years from 1981 through the end of the 2007 growing season, 258 distinct plots were repeatedly measured (some plots one, two, three, or four times) to produce a total of 638 plot/stand level observations that included 29,244 measured trees, 2103 professionally graded trees, and 9,985 total and merchantable height measurements. Grade distribution measurements were recorded on most of the plots.

Table 1 Site index frequency table for red oak species found in the permanent growth and yield study plots in Mississippi and Alabama (reproduced from Schultz et al. 2010).

	Site index (base age 50 years)							
Age class	70	80	90	100	110	120	130^+	All
20	1	1	2	6	8	1	1	20
30	0	2	6	15	31	6	0	60
40	1	3	20	42	49	21	4	140
50	0	4	24	57	52	14	2	153
60	1	1	14	56	42	8	5	127
70	0	0	7	32	32	11	2	84
80	0	1	4	19	11	6	0	41
90^+	0	0	2	6	5	0	0	13
All	3	12	79	233	230	67	14	638

Growth and Yield Measurements

Measurements were obtained on all 3.6" dbh and greater trees as reported by (Iles 2008) were:

1. Species,

2. Dbh to 0.1",
3. Crown class,
4. Butt log grade,
5. Azimuth and distance from plot center, and
6. GPS coordinates of plot center monument (beginning with the 2005 remeasurements).

on a balanced subsample of ten plot trees selected across dbh classes and species:

1. Total height,
2. Merchantable height,
3. Height to an 8” top, and
4. Height to a 4” top

on all ingrowth trees:

1. Tagged all trees 4" dbh and greater not recorded last measurement and
2. Azimuth, distance from plot center, and dbh for each ingrowth tree.

and site index data recorded on six dominant or codominant red oak trees were:

1. Age, and
2. Total height.

Grade Distribution Measurements

Trees were selected for grading from the same balanced subset of plot trees used for total and merchantable height measurement. Graded trees were required to possess a minimum dbh of 9.6 inches and merchantable volume. Measurements as reported by (Banhzaf 2009) were:

1. Dbh,

2. Total height,
3. Height to first dead limb,
4. Height to first live limb,
5. Stump height,
6. Section grade for each merchantable log in tree,
    a. Length,
    b. Grade, and
    c. Stopper code
7. Epicormic branches, and
    a. Frequency on lower bole and
    b. Frequency on upper bole
8. Final merchantable stopper code.

Growth and Yield System Structure

Moment recovery models (Matney and Sullivan 1982; Matney et al. 1990) were developed using stand level prediction equations presented by Iles (2008). Diameter distribution models were constructed using least squares moment recovery models, parameter recovery techniques, and least squares adjustment procedures (Burden et al. 1981; Farrar and Matney 1994; Matney and Farrar 1992) bounded and reconciled by Iles' (2008) stand level models. A parameter free least squares moment recovery model (Matney et al. 1990) was used when inputs to the growth and yield system included a tree list from an existing inventory (Table 2). In the case where there is no tree list but age, site index (SI), trees per acre (TPA), QD, and AD are supplied (Table 3), a Weibull probability model was applied to recover the moments (AD and QD) of the dbh distribution (Matney and Sullivan 1982). TPA adjusted for mortality was multiplied by the Weibull diameter distribution to generate diameter classes for each tree species group from which stand and stock tables can be generated.

Table 2 Diameter distribution growth and yield system structure for the scenario where stand level equations are used to update future diameter distributions (tree list).

Step	Input Information	Calculations
1a	Age, SI, tree list	Construct stand and stock table from existing inventory. QD, AD & TPA are calculated from tree list to get diameter distribution at starting age.
1b	Age, SI, TPA, QD, AD	Weibull diameter distribution recovery method is used to produce diameter distribution using input QD and AD. Multiply input TPA times the proportion of trees in each diameter class (produced from the Weibull distribution) to get total TPA in each diameter class. This procedure produces initial stand and stock table.
2		Use stand level growth equations for QD, AD, and TPA developed by Iles(2008).
3		Update tree list by using least squares recovery methods to project a stand and stock table from the previous stand and stock table that has the same QD, AD, and TPA as projected in step 2. This reconciles the tree list with the stand level equations. It is important to choose good weighting functions in this process.
4		Repeat steps 2 and 3 for an average growth cycle of every 8 years (average remeasurement cycle for this study).
5		Predict heights from Iles (2008) individual tree height equation and use to calculate volumes and biomass. Volumes by grade are calculated using equations from Banzhaf (2009).

Table 3 Diameter distribution growth and yield system structure for the scenario where individual tree equations are applied to update future diameter distributions (tree list).

Step	Input Information/Level	Calculations
1a	Age, SI, TPA, QD, AD	Weibull diameter distribution recovery method is used to produce diameter distribution using input QD and AD. Multiply input TPA times the proportion of trees in each diameter class (produced from the Weibull distribution) to get total TPA in each diameter class. This procedure produces initial stand and stock table.
1b	Age, SI, tree list	Construct stand and stock table from existing inventory. QD, AD & TPA are calculated from tree list to get diameter distribution at starting age.
2	Individual tree	Apply individual tree growth equations and survival function to update tree list.
3	Individual tree	Repeat steps 1 and 2 for an average growth cycle of every 8 years (average remeasurement cycle for this study) until reach projected age.
4		Predict heights from Iles (2008) individual tree height equation and use to calculate volumes and biomass for both stand level and individual tree estimates. Volumes by grade are calculated using equations from Banzhaf (2009).

Stand and Growth Equations

The stand level prediction models by Iles (2008) were refined and additional growth and mortality functions (Matney et al. 1990) were developed for incorporation into the growth and yield system (Tables 2 and 3). Growth equations produce QD and AD projections and mortality functions produce TPA projections. Growth models were designed for individual tree species as well as combined species based on age, initial dbh, TPA, and HD. The dominant term for the diameter growth equation (RDG) in Equation 1 is the c parameter which is initial dbh divided by age times the quadratic diameter.

$$RDG = a + bD_0 + c\left[\frac{D_0}{A_0(QD)}\right] + d\left(\frac{TPA}{D_0}\right) + e(HD) + f\left(\frac{1}{A_0(D_0)}\right) \qquad (1)$$

where RDG = $\frac{D_1 - D_0}{A_1 - A_0 \quad D_0} 100 =$ relative diameter growth associated with the

equationequation parameters; D_0 (dbh) = current or time 0 dbh measurement of tree; D_1 (dbh) = future or time 1 dbh measurement of tree at time 1; A_0 (age) = average age red oaks at time 0; A_1 (age) = average age of red oaks at time 1; QD = quadratic mean dbh of all tress for combined species; TPA = trees/ac of all trees for combined species; HD = average height of dominant and codominant red oaks; and a, b, c, d, e, and f are parameters to be estimated from the data (Table 4).

Survival Equations

Survival model equations were developed to predict TPA projections. Survival models were designed for individual tree species as well as all species combined based on dbh, QD, initial age, HD, and future age. The best logistic survival model developed was

$$P(Survival / X) = \frac{1}{1+e^{-s}} 100 \qquad (2)$$

where P(Survival/X) = the probability of survival,

$$S = a + b\frac{D_0}{QD} + c\frac{1}{A_0} + d(\ln HD) + e\left(\frac{\ln HD}{A_0}\right) + f\left(\frac{D_0}{QD_0}\right)\left(\frac{1}{A_0}\right) + g\left(A_1 - A_0\right) = \qquad (3)$$

and a, b, c, d, e, f, and g are parameters to be estimated from the data (Table 5).

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Validation

Validation was conducted to see how well the survival and growth equations performed in the model using average bias and precision equations.

$$\text{Bias} = \frac{\sum_{i=1}^{n}\left(y_i - (\hat{y}_i)\right)}{n} \tag{4}$$

$$\text{Precision} = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - (\hat{y}_i)\right)^2}{n}} \tag{5}$$

where

y_i = observed,

$\hat{y}_i$ = estimated, and

n = number of observations

The results of validation are given in Tables 6 – 13.

CHAPTER III

RESULTS AND DISCUSSION

Growth Model

The parameter estimates and fit statistics for the tree diameter growth model are given in Table 4. Study criteria specified percentages of red oaks and sweetgum observations for plots within the red oak-sweetgum forest types consequently resulting in higher numbers of observations for the two species. Because red oaks and sweetgums are the predominant stand species and occur across the spread of crown classes and tend to occur more frequently in the dominant and codominant categories, they exhibit more variability than other species. The other species tend to occur more in the intermediate and suppressed crown categories and exhibit less variability. Therefore, the regression for the other species tends to have lower R^2's even though the precision of estimate as measured by the standard error of predictions are nearly the same.

Table 4 Percentage annual diameter growth parameter estimates and fit statistics for Equation 1 of red oak-sweetgum forest mixtures in Mississippi and Alabama minor stream bottoms

Species equations	Tree diameter growth parameter estimates						Fit statistics	
	a	*b*	*c*	*d*	*e*	*f*	Std. error	R^2%
			·····Combined species·····					
All	1.186600	0.033402	17.473600	0.014068	-0.001474	85.256000	0.8697	13.3
			·····Individual species·····					
RO	2.380000	0.018144	20.462000	0.011960	-0.014553	137.660000	0.7462	32.7
WO	1.659800	0.024070	-0.069000	0.005766	-0.002440	13.440000	0.7754	1.8
SG	0.528900	0.016149	11.259000	0.008258	0.000055	35.777000	0.6562	11.9
HK	1.434000	0.052820	10.666000	0.001057	-0.001810	107.660000	0.9741	3.8
OC	1.449500	0.057680	9.585000	0.006258	-0.000115	34.830000	1.0352	2.6
NC	1.906800	0.139150	0.254000	0.005305	0.002097	9.730000	1.0238	6.2

Survival Model

Logistic regression procedures were employed to obtain a probability of survival model for each species group. The best logistic probability survival model developed from the data variables was Equation 2. The coefficients for the survival model are given in Table 5. The concordances (Allison 1999; Holander 1999) of predictions for all species groups were very good with the number of discordant groups very small.

Table 5 Species survival parameter estimates and fit statistics for Equation 2 in red oak-sweetgum forest mixtures in Mississippi and Alabama minor stream bottoms

Species equations	Species survival parameters							Fit statistics measures of association		
	a	*b*	*c*	*d*	*e*	*f*	*g*	Concordant %	Discordant %	Ties%
				····················Combined species····················						
All	-6.79799	-1.85068	174.90700	2.36604	-60.45150	141.70000	-0.15041	71.3	28.2	0.5
				····················Individual species····················						
RO	-1.88176	-1.28222	176.53100	1.11634	-64.81440	149.45600	-0.15743	77.9	21.8	0.3
WO	-43.39470	1.14949	1463.99000	9.77713	-320.12300	12.47960	-0.08831	68.5	30.7	0.9
SG	-18.42750	0.00282	501.86800	4.60012	-127.19400	129.02800	-0.16732	76.5	23.1	0.4
HK	-1.16481	-3.14981	-222.52900	1.13415	40.88200	147.76500	-0.15386	69.2	29.9	0.9
OC	-2.15095	-1.41944	144.49000	1.48983	-54.21100	93.23440	-0.15801	67.5	31.8	0.6
NC	0.91691	-1.00123	-87.71370	0.39760	21.10410	2.17148	-0.01168	64.8	34.5	0.7

Validation

Results of the validation procedure are given in Tables 6 – 13. Since there are no comparable results reported in the literature, they form a basis for future comparison. Estimates of individual tree bias in Table 13 are reasonably low based in the experience of the author.

Table 6 Sample size, bias, and root mean square error of diameter growth and survival model for red oak species

		Diameter growth			Survival		
Species	Dbh (in.)	Sample size N	Bias[1]	RMSE	Sample size N	Bias[2]	RMSE
RO	4	119	0.8608	1.6998	96	-0.0464	0.7784
RO	5	126	0.5454	1.3958	128	-0.1125	0.7941
RO	6	174	0.2489	1.031	142	-0.1321	0.7184
RO	7	171	0.1303	1.0986	145	-0.0431	0.4901
RO	8	190	-0.1775	0.8922	148	-0.0024	0.4911
RO	9	203	-0.331	0.8774	167	-0.0034	0.4383
RO	10	262	-0.3239	0.9197	191	0.0716	0.4113
RO	11	229	-0.4339	0.9661	182	0.0291	0.3773
RO	12	254	-0.5337	0.9492	174	0.0481	0.3464
RO	13	244	-0.5386	0.9894	168	0.0604	0.3805
RO	14	224	-0.6966	1.2221	167	0.0555	0.3418
RO	15	185	-0.7305	1.0596	157	-0.0131	0.3727
RO	16	172	-0.8566	1.2253	138	-0.0036	0.4286
RO	17	151	-0.8168	1.2053	126	0.0426	0.312
RO	18	121	-0.7098	1.0008	94	0.0757	0.3263
RO	19	110	-0.8876	1.2357	107	-0.0476	0.3822
RO	20	115	-0.7517	1.0484	97	0.0459	0.3238
RO	21	90	-0.8943	1.2603	84	-0.0169	0.3352
RO	22	73	-0.5958	0.8805	62	0.0617	0.3553
RO	23	76	-0.7292	1.0349	71	0.0236	0.3144
RO	24	61	-0.9384	1.2606	61	-0.0776	0.4321
RO	25	63	-0.8963	1.1565	54	0.0593	0.2533
RO	26	51	-0.9773	1.1676	50	-0.087	0.4026
RO	27	42	-0.9652	1.1854	40	-0.0225	0.4179
RO	28	18	-0.7004	0.8637	19	0.0038	0.2887
RO	29	22	-1.2089	1.3978	23	-0.0507	0.3214
RO	30	71	-1.3166	1.5268	58	-0.1392	0.4379
RO	All dbh	3617	-0.4599	1.1078	378	-0.0017	1.5381

1) $Bias\ \ Growth\ = observed - predicted$

2) $Bias\ \ Survival\ = observed\ /\ acre\ survival - predicted\ /\ acre\ survival$

Table 7 Sample size, bias, and root mean square error of diameter growth and survival model for white oak species

		Diameter growth			Survival		
Species	Dbh (in.)	Sample size N	Bias[1]	RMSE	Sample size N	Bias[2]	RMSE
WO	4	53	1.0171	1.4846	43	-0.0435	0.5772
WO	5	73	0.6053	0.9279	58	-0.0863	0.5598
WO	6	59	0.4904	0.9757	50	-0.0397	0.5037
WO	7	60	0.1127	0.81	49	0.1146	0.3689
WO	8	50	0.1189	0.6753	40	0.084	0.3529
WO	9	37	0.0699	0.9257	39	-0.0514	0.3602
WO	10	27	-0.0562	0.5873	26	0.0327	0.2878
WO	11	23	0.0594	0.6035	20	0.0704	0.1744
WO	12	16	-0.0173	0.429	14	0.0907	0.1198
WO	13	9	-0.0986	0.439	9	0.0764	0.0886
WO	14	8	-0.2614	0.6673	10	-0.1163	0.4086
WO	15	8	0.0283	0.792	8	0.0569	0.0679
WO	16	9	-0.3936	0.5416	8	-0.0388	0.2973
WO	17	4	-0.7487	1.176	5	-0.1666	0.4184
WO	18	10	-0.4351	0.5648	9	-0.0537	0.3229
WO	19	7	-0.7774	0.8847	7	0.0508	0.0569
WO	20	3	-0.293	0.6902	3	0.0192	0.0215
WO	21	4	-0.6614	0.8086	4	0.0406	0.0428
WO	22	3	-0.6065	0.6484	3	0.025	0.0269
WO	23	0	0	0	0	0	0
WO	24	1	-0.2397	0.2397	1	0.0137	0.0137
WO	25	1	-0.598	0.598	1	0.0427	0.0427
WO	26	2	-0.7257	0.7381	2	0.0231	0.0238
WO	27	0	0	0	0	0	0
WO	28	1	-0.5163	0.5163	1	0.0371	0.0371
WO	29	1	-1.4766	1.4766	1	0.0128	0.0128
WO	30	3	-1.9273	2.1484	4	-0.2421	0.4981
WO	All Dbh	472	0.2275	0.9213	171	-0.001	0.6295

1) $Bias\ \ Growth = observed - predicted$

2) $Bias\ \ Survival = observed / acre\,survival - predicted / acre\,survival$

Table 8 Sample size, bias, and root mean square error of diameter growth and survival model for sweetgum species

		Diameter Growth			Survival		
Species	Dbh (in.)	Sample Size N	Bias[1]	RMSE	Sample Size N	Bias[2]	RMSE
SG	4	1468	0.216	0.8475	275	5.216	7.9702
SG	5	1353	0.1219	0.6971	281	4.6503	6.8726
SG	6	1028	0.0342	0.6724	294	3.3432	4.6144
SG	7	864	0.0069	0.6163	292	2.7858	3.7963
SG	8	597	0.0125	0.6067	272	2.0403	2.6891
SG	9	578	0.0222	0.5793	265	1.9993	2.5057
SG	10	467	-0.0464	0.5045	238	1.7845	2.2913
SG	11	327	-0.0755	0.4834	196	1.5092	1.8608
SG	12	233	-0.0843	0.4706	156	1.3396	1.6013
SG	13	245	-0.0443	0.5318	154	1.4042	1.6986
SG	14	210	-0.1427	0.4767	151	1.2382	1.4786
SG	15	153	-0.127	0.4734	106	1.2744	1.5097
SG	16	113	-0.1104	0.4799	84	1.1677	1.3861
SG	17	80	-0.0897	0.4543	71	0.9815	1.2378
SG	18	50	-0.1785	0.4109	49	0.8664	0.9899
SG	19	45	-0.2594	0.4223	38	1.0007	1.0955
SG	20	34	-0.1604	0.4379	31	0.8875	0.9804
SG	21	18	-0.1487	0.5056	19	0.7686	0.831
SG	22	12	-0.2577	0.3863	13	0.7149	0.7815
SG	23	10	-0.4855	0.5105	10	0.785	0.8254
SG	24	5	-0.4046	0.4208	5	0.7295	0.8059
SG	25	7	-0.3908	0.5117	6	1.0537	1.1207
SG	26	7	-0.5361	0.5908	6	0.8971	1.0788
SG	27	1	-0.4001	0.4001	1	0.2661	0.2661
SG	28	0	0	0	0	0	0
SG	29	1	-0.5194	0.5194	1	1	1
SG	30	5	-0.4477	0.47	6	0.6856	0.7773
SG	All Dbh	7911	0.0441	0.6554	381	19.4706	24.2389

1) $Bias\ \ Growth = observed - predicted$

2) $Bias\ \ Survival = observed / acre\ survival - predicted / acre\ survival$

Table 9 Sample size, bias, and root mean square error of diameter growth and survival model for hickory species

		Diameter Growth			Survival		
Species	Dbh (in.)	Sample Size N	Bias[1]	RMSE	Sample Size N	Bias[2]	RMSE
HK	4	320	0.6518	1.4919	146	-0.4247	0.9363
HK	5	165	0.5151	1.0191	109	-0.1597	0.6417
HK	6	129	0.3558	0.7627	79	0.0695	0.8296
HK	7	67	0.1921	0.5821	54	0.0362	0.6618
HK	8	52	0.2487	0.8147	47	0.2136	0.6435
HK	9	37	-0.0669	0.8117	30	0.6677	1.1218
HK	10	28	0.0078	0.6571	32	0.4503	0.8448
HK	11	24	-0.0787	0.7401	18	0.9931	1.2913
HK	12	15	-0.0734	0.4779	14	1.0714	1.165
HK	13	30	-0.3066	0.6049	27	1.001	1.2322
HK	14	12	-0.4684	0.8648	15	0.6887	0.8178
HK	15	6	-0.3034	0.8243	7	0.8571	0.9258
HK	16	3	-0.6953	0.962	3	1	1
HK	17	3	-0.3039	0.4881	5	0.6	0.7746
HK	18	8	-0.4558	0.5724	7	1.1429	1.1952
HK	19	4	-0.2912	0.3418	5	0.8	1.0954
HK	20	3	-0.5615	0.6374	4	0.75	0.866
HK	21	3	-0.0479	0.4921	3	1	1
HK	22	1	-0.2957	0.2957	3	0.3333	0.5774
HK	23	1	-0.7753	0.7753	1	1	1
HK	24	2	-0.1245	0.1482	2	1	1
HK	25	0	0	0	0	0	0
HK	26	1	-1.1355	1.1355	1	1	1
HK	27	0	0	0	1	0	0
HK	28	0	0	0	1	0	0
HK	29	1	-1.1688	1.1688	1	1	1
HK	30	0	0	0	0	0	0
HK	All Dbh	915	0.3608	1.0989	211	0.3732	1.7449

1) $Bias\ \ Growth\ = observed - predicted$

2) $Bias\ \ Survival\ = observed / acre\ survival - predicted / acre\ survival$

Table 10 Sample size, bias, and root mean square error of diameter growth and survival model for all other commercial species

		Diameter growth			Survival		
Species	Dbh (in.)	Sample size N	Bias[1]	RMSE	Sample size N	Bias[2]	RMSE
OC	4	376	0.7086	1.4257	198	1.899	2.5166
OC	5	227	0.6468	1.4099	166	1.3675	1.7818
OC	6	203	0.3037	1.051	152	1.3355	1.6956
OC	7	139	0.2071	0.9513	126	1.1032	1.3363
OC	8	101	0.1063	0.8121	94	1.0745	1.259
OC	9	74	0.0699	0.7538	67	1.1045	1.2813
OC	10	61	-0.0931	0.8545	55	1.0882	1.3465
OC	11	60	-0.0405	0.8658	50	1.1842	1.4074
OC	12	34	-0.1906	0.7547	32	0.9685	1.0751
OC	13	24	-0.2863	0.7206	23	0.6087	0.8341
OC	14	27	-0.3978	0.7378	29	0.6439	0.9668
OC	15	16	-0.4427	0.7402	18	0.6621	0.8769
OC	16	7	-0.2592	0.5605	10	0.3002	0.8364
OC	17	10	-0.5382	0.8993	11	0.7281	0.8528
OC	18	9	-0.7519	0.9482	12	0.1926	0.6727
OC	19	11	-0.5953	0.9309	13	0.0768	0.733
OC	20	6	-1.0286	1.376	6	0.1667	0.4082
OC	21	7	-0.7661	0.8203	7	0.2862	0.5345
OC	22	6	-0.2554	0.5036	6	0.6655	0.815
OC	23	2	-0.3148	0.3726	4	-0.2499	0.866
OC	24	1	-0.3886	0.3886	1	0	0
OC	25	2	-0.3207	0.4661	2	0.5	0.7071
OC	26	2	-0.6685	0.6784	2	0	0
OC	27	2	-0.0738	0.3208	2	0.7548	0.7936
OC	28	1	-0.1096	0.1096	1	0.9962	0.9962
OC	29	0	0	0	0	0	0
OC	30	1	-2.8415	2.8415	1	0	0
OC	All Dbh	1409	0.3127	1.1534	331	4.0437	5.7342

1) $Bias\ \ Growth\ = observed - predicted$

2) $Bias\ \ Survival\ = observed / acre\ survival - predicted / acre\ survival$

Table 11 Sample size, bias, and root mean square error of diameter growth and survival model for all non-commercial species

		Diameter growth			Survival		
Species	Dbh (in.)	Sample size N	Bias[1]	RMSE	Sample size N	Bias[2]	RMSE
NC	4	589	0.8746	1.464	254	-0.5472	1.0443
NC	5	348	0.6487	1.2379	191	-0.4346	0.8407
NC	6	171	0.2848	0.7713	144	-0.3611	0.7817
NC	7	84	0.3669	0.9016	84	-0.2332	0.5959
NC	8	63	0.2865	0.971	54	-0.1269	0.5258
NC	9	33	0.1192	0.7041	42	-0.2693	0.698
NC	10	30	0.0265	0.5903	27	-0.1184	0.643
NC	11	9	-0.188	0.6068	14	0.1534	1.0694
NC	12	9	-0.0875	0.3972	13	0.3477	0.7903
NC	13	4	-0.391	0.6889	7	0.1601	0.8537
NC	14	4	-0.1015	0.5869	5	0.1442	0.7158
NC	15	5	-0.3009	0.4019	8	0.295	0.5159
NC	16	3	0.3106	0.7094	5	0.6	0.7746
NC	17	1	-0.5508	0.5508	3	0.3333	0.5774
NC	18	0	0	0	1	0	0
NC	19	1	-0.4461	0.4461	3	0.3333	0.5774
NC	20	0	0	0	1	0	0
NC	21	0	0	0	1	0	0
NC	22	0	0	0	0	0	0
NC	23	0	0	0	0	0	0
NC	24	0	0	0	0	0	0
NC	25	0	0	0	0	0	0
NC	26	0	0	0	0	0	0
NC	27	0	0	0	0	0	0
NC	28	0	0	0	0	0	0
NC	29	0	0	0	0	0	0
NC	30	0	0	0	0	0	0
NC	All Dbh	1354	0.6183	1.2343	313	-0.9555	1.9254

1) $Bias\ \ Growth\ = observed - predicted$

2) $Bias\ \ Survival\ = observed\,/\,acre\ survival - predicted\,/\,acre\ survival$

Table 12 Sample size, bias, and root mean square error of diameter growth and survival model for all species combined

		Diameter growth			Survival		
Species	Dbh (in.)	Sample size N	Bias[1]	RMSE	Sample size N	Bias[2]	RMSE
All species	4	2925	0.5003	1.2059	379	4.2298	7.4027
All species	5	2292	0.3209	0.9621	370	3.8214	6.3779
All species	6	1764	0.1494	0.7921	371	3.0152	4.5679
All species	7	1385	0.0776	0.7556	363	2.5735	3.7801
All species	8	1053	0.0203	0.7255	353	1.8758	2.7205
All species	9	962	-0.0469	0.695	329	1.854	2.5049
All species	10	875	-0.1288	0.6903	329	1.5511	2.272
All species	11	672	-0.1915	0.7319	314	1.2157	1.7593
All species	12	561	-0.2921	0.7405	288	0.9345	1.3883
All species	13	556	-0.2892	0.7765	283	0.9513	1.4735
All species	14	485	-0.4224	0.9204	263	0.8547	1.3245
All species	15	373	-0.4417	0.8359	230	0.6685	1.1513
All species	16	307	-0.5418	0.9776	198	0.5367	1.0085
All species	17	249	-0.5636	1.003	183	0.4712	0.8839
All species	18	198	-0.5534	0.8515	143	0.4153	0.7718
All species	19	178	-0.6905	1.0377	146	0.269	0.7321
All species	20	161	-0.625	0.9553	119	0.3027	0.6337
All species	21	122	-0.7485	1.1294	105	0.1748	0.5066
All species	22	95	-0.5288	0.803	81	0.2245	0.5448
All species	23	89	-0.693	0.9766	79	0.1206	0.4758
All species	24	70	-0.8592	1.1837	68	0.0137	0.4979
All species	25	73	-0.828	1.091	60	0.1761	0.4829
All species	26	63	-0.913	1.093	57	0.0365	0.5353
All species	27	45	-0.913	1.1488	42	0.0209	0.4567
All species	28	20	-0.6616	0.8278	20	0.0553	0.4052
All species	29	25	-1.1904	1.3682	25	0.0338	0.4185
All species	30	80	-1.3042	1.5351	64	-0.077	0.4819
All species	All Dbh	15678	0.0256	0.9203	382	22.3446	27.1934

1) $Bias\ \ Growth\ = observed - predicted$

2) $Bias\ \ Survival\ = observed / acre\, survival - predicted / acre\, survival$

Table 13 Sample size, bias, and root mean square error for diameter growth and survival model for all sample size combined by species class.

Species	Diameter Growth Sample size N	Diameter Growth Bias[1]	Diameter Growth RMSE	Survival Sample size N	Survival Bias[2]	Survival RMSE
All Species	15678	0.0256	0.9203	382	0.0585	-1.3913
RO	3617	-0.4599	1.1078	378	-0.0017	1.5381
WO	472	0.2275	0.9213	171	-0.001	0.6295
SG	7911	0.0441	0.6554	381	0.0511	1.2418
HK	915	0.3608	1.0989	211	0.3732	1.7449
OC	1409	0.3127	1.1534	331	4.0437	5.7342
NC	1354	0.6183	1.2343	313	-0.9555	1.9254

1) $Bias\ \ Growth\ = observed - predicted$

2) $Bias\ \ Survival\ = observed\,/\,acre\,survival - predicted\,/\,acre\,survival$

Example

Consider the prediction of the diameter growth and survival of a red oak 12 inches in dbh in a 60 year old stand with 200 trees per acre. The first step is to estimate RDG by using Equation 1 and the regression coefficients given in Table 3.

$$RDG = 2.38 + -0.018144(12) + 20.462\left[\frac{12}{60\ \ 11.95}\right] + -0.011960\left(\frac{200}{12}\right) + 0.014525\ \ 125\ \ +137.66\left(\frac{12}{60\ \ 12}\right) = .6809683624 \tag{6}$$

From the definition of RDG in Equation 1, the future diameter, D_1, after rearranging to solve for D_1 is

$$D_1 = D_0\left[1 + \frac{A_1 - A_0\ \ RDG}{100}\right] = 12\left[1 + \frac{65 - 60\ \ RDG}{100}\right] = 12.408576 \tag{7}$$

From Equation 2 and coefficients in Table 5, the probability of the tree surviving 5 years is calculated by the equation.

$$S = -1.88176 + -1.28222\frac{12}{11.95} + 176.531\frac{1}{60} + 1.11634(\ln 125) + -64.8144\left(\frac{\ln 125}{60}\right) + 149.456\left(\frac{12}{11.95}\right)\left(\frac{1}{60}\right) + -0.15743(65-60) = 1.644679511 \quad (8)$$

$$P(Survival / X) = \frac{1}{1+e^{-1.644679511}}100 = 83.817 \quad (9)$$

A C++ program was used to access the bias and precision of the individual tree diameter growth and survival model. Table 13 shows the average bias and root mean square error for prediction of future arithmetic and quadratic mean dbh and TPA for each remeasurement.

CHAPTER IV

SUMMARY

The equations developed and tested here will be incorporated into the growth component of the currently available stand level model at www.timbercruise.com (Schultz et al. 2010). Testing the equations inside the existing growth and yield system indicates that they behave well and give logical and reasonably precise predictions of stand growth and survival. The diameter distribution model along with the TPA survival model will allow for future calculation of TPA by diameter class in stand and stock tables for inventories by species, size class, product, and grade.

The diameter distribution and TPA survival models developed here, along with the stand level equations and volume prediction models, will be the basis of a web based growth and yield model system for southern bottomland hardwoods will be provided to the public via the web. This system will aide landowners in making management decisions.

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